

## Pentaquark candidates $P_c^+(4380)$ and $P_c^+(4450)$ within the soliton picture of baryons

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Using the bound state version of the topological soliton model for the baryons we show that the existence of a bound (or quasibound)  $\bar{D}$ -soliton state leads to the possibility of having hidden charm pentaquarks with quantum numbers and masses, which are compatible with those of the candidates recently reported by the LHCb experiment. The implications of heavy quark symmetry are elaborated.

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### I. INTRODUCTION

The LHCb collaboration at CERN recently reported the discovery of two states, which in the quark model correspond to “pentaquarks” with hidden charm Ref. [1]. The first one has the mass (width)  $4380 \pm 8 \pm 29$  ( $205 \pm 18 \pm 86$ ) MeV and the second the mass (width)  $4449.8 \pm 1.7 \pm 2.5$  ( $39 \pm 5 \pm 19$ ) MeV. The preferred quantum number assignments are  $J^\pi = 3/2^-, 5/2^+$ , respectively, although acceptable solutions are also found for additional cases with opposite parity. Note that their decay channel is  $J/\psi p^+$  which implies  $I = 1/2$ . After this announcement several articles that consider possible theoretical interpretations of the observed states have appeared. Some of these [2–5] suggest, with some variations, that the observed states may be interpreted as anticharmed meson ( $\bar{D}$  or  $\bar{D}^*$ )-hyperon ( $\Sigma$  or  $\Sigma^*$ ) molecular states, while others base their description on diquark models [6–9]. The possibility that at least one of the observed peaks might be only a kinematical effect was discussed in Refs. [10–12]. Further suggestions have been put forward in Refs. [13,14]. Moreover, the production and formation of the hidden-charm pentaquarks in  $\gamma$ -nucleon collisions have been discussed in Refs. [15,16].

The purpose of the present paper is to show that it is also possible to account for the quantum numbers and masses of these observed pentaquark candidates within the topological soliton picture of baryons. The possible existence of stable pentaquarks with negative charm in that framework was already considered many years ago [17]. In this approach the heavy flavor hyperons were described as bound states of heavy flavor mesons and a topological soliton [17–19] in the extension to heavy flavor of the bound state approximation [20–22] to the Skyrme model, supplemented with suitable symmetry breaking terms. This “naive Skyrme model” (NSM) formulation does however only approximately [23] incorporate heavy quark

symmetry (HQS) according to which in the heavy quark limit the heavy pseudoscalar and vector fields become degenerate and, therefore, should be treated on an equal footing [24]. An improved way to proceed is therefore to apply the bound state approach to the heavy meson effective Lagrangian [25–28], which simultaneously incorporates chiral symmetry and heavy quark symmetry (for details see Ref. [29] and refs. therein). The possible existence of a  $C = -1$  meson bound state in the context of a model consistent with HQS was first discussed in Refs. [30,31]. There, however, only pseudoscalar mesons as described by the Skyrme model were considered in the light sector. In what follows we will refer to this as SMHQS formulation. It was later pointed out [32] that the inclusion of light vector mesons in the corresponding effective Lagrangian tends to push this state into the continuum. On other hand, the calculation in Ref. [33], which incorporates the center of mass corrections in a more consistent way, still leaves the possibility of a loosely bound state. Additional arguments for the existence of  $C = -1$  meson-soliton bound state have been given in Ref. [34].

In the NSM approach it is the Wess-Zumino term in the Lagrangian, which is responsible for the difference in the interaction of the soliton and the mesons with opposite massive flavor quantum number. This term is repulsive in the case of mesons with massive antiflavor quantum number. In the case of  $S = +1$  kaons, this repulsion, in combination with the repulsive effect of the meson kinetic energy term, pushes them into the continuum [35,36]. (It should here be mentioned that the indications for the existence of the conjectured strange pentaquark “ $\theta(1540)$ ” [37] have hitherto not been experimentally confirmed [38]). As the repulsive effect of the kinetic energy term weakens with increasing meson mass and the strength of the Wess-Zumino term is smaller for heavy flavors, the existence of anticharm (and *a fortiori* anti-bottom) meson-soliton bound states becomes possible.

Below we show that the existence of a bound (or quasi-bound state)  $\bar{D}$ -soliton state naturally leads to the possibility of having some hidden charm pentaquarks with quantum numbers and masses which are compatible with those of the candidates proposed in Ref. [1]

## II. BOUND STATE DESCRIPTION OF HIDDEN HEAVY FLAVORED PENTAQUARKS

Since the pentaquark candidates reported in Ref. [1] have no net charm quantum number we propose to describe them as bound states of a soliton and two pseudoscalar mesons (one charm and the other anticharm) in the present picture. We recall that soliton models are based on effective Lagrangians in which mesons are taken to be elementary degrees of freedom. Therefore, the determination of the quark content of a given baryon state is not that straightforward, and has to be done only at the level of quantum numbers. Thus, in the bound state approximation, while a bound  $C = +1$  meson behaves as a quark [18–22], a  $\bar{D}$ -meson corresponds to a antiheavy-light quark pair [17,30,31]. To determine the possible quantum numbers and estimate the values of the associated masses we need to know which bound states of charm and anticharm mesons are possible. In fact, both the NSM and the SMHQS models lead to a number of meson bound states. Those bound states can be labeled by  $k^\pi$ , where  $\vec{k} = \vec{i} + \vec{\ell}$  and  $\pi = (-1)^{\ell+1}$ . Here,  $\ell$  and  $i = 1/2$  are the angular momentum and isospin of the bound pseudoscalar meson. In Table I the corresponding quantum numbers, binding energies  $b$  and hyperfine splittings constants  $c$  are given. The latter are needed for calculation of the nonadiabatic corrections to be discussed below. Note that in the case of the  $(C, l, k^\pi) = (+1, 1, 1/2^+)$  channel, in addition to the ground state, the first radial excitation is also bound. These results were obtained using the standard Skyrme model parameters  $f_\pi = 64.5$  MeV,  $e = 5.45$ , which lead to the empirical masses for the nucleon and the  $\Delta$  resonance. The values of the binding energies  $b$  and hyperfine splittings  $c$  associated with the  $C = \pm 1$  mesons in the NSM scheme have been calculated in Refs. [17,19]. Those of the SMHQS scheme have been extracted from Ref. [39] (Set 5) except for the binding of the  $C = -1$  state, which is taken from Ref. [33].

TABLE I. Quantum numbers of the meson bound states and associated binding energies and hyperfine splitting constants.

	$l$	$k^\pi$	NSM		SMHQS	
			$b(\text{MeV})$	$c$	$b(\text{MeV})$	$c$
$C = +1$	1	$1/2^+$	568	0.20	518	0.15
	0	$1/2^-$	355	0.52	239	0.30
	2	$3/2^-$	243	0.15	212	
	1	$3/2^+$	140	0.28	49	
	1	$1/2^+$	118	0.03	65	
$C = -1$	1	$1/2^+$	38	0.16	54	

Note that most of the associated hyperfine splittings have not been given in those works, however. The results corresponding to the NSM have been obtained using the decay constant ratio  $f_D/f_\pi = 1.8$ . This value has been updated in recent years. The current estimate is  $f_D/f_\pi = 1.57$  [40]. While the use of this value hardly affects the predictions for the hyperfine splitting constants, one obtains an enhancement of about 100 MeV for all the  $C = +1$  binding energies. Since the results for the binding energies obtained with  $f_D/f_\pi = 1.8$  are closer to those of the SMHQS formulation we will assume that this over-binding is a consequence of the simplicity inherent to the NSM formulation.

The single meson spectra that follow from Table I are illustrated in Fig. 1. It can be seen that the meson spectrum obtained in the NSM formulation is qualitatively similar to that obtained using the SMHQS formulation. Actually, this fact was already noticed long ago [23].

Clearly, the  $C = -1$  meson has to be bound in the  $k_-^\pi = 1/2^+$  state. Here, the subindex stands for the charm quantum number of the meson. For the  $C = +1$  one, we have, however, several possibilities. The preferred quantum number assignments of the pentaquark candidates are  $J^\pi = 3/2^-, 5/2^+$ , respectively. Since, obviously,  $\pi = \pi_- \pi_+$  it follows that  $\pi_+ = -(+)$  for the  $3/2^-$  ( $5/2^+$ ) pentaquarks. To determine  $k_+$  we note that, according to the usual rules, the total grand spin  $\vec{K} = \vec{k}_+ + \vec{k}_-$  satisfies  $\vec{K} = \vec{J} + \vec{I}$  where  $J$  and  $I$  are the total spin and isopin of the bound system. Noting that the observed states are isospin doublets, it follows that  $1/2 \leq k_+ \leq 5/2$  for the state with  $J = 3/2$  and  $3/2 \leq k_+ \leq 7/2$  for that with  $J = 5/2$ . From Fig. 1 it is clear that the lowest lying meson configurations ( $k_+^\pi, k_-^\pi$ ) that satisfy all the requirements are  $(1/2^-, 1/2^+)$

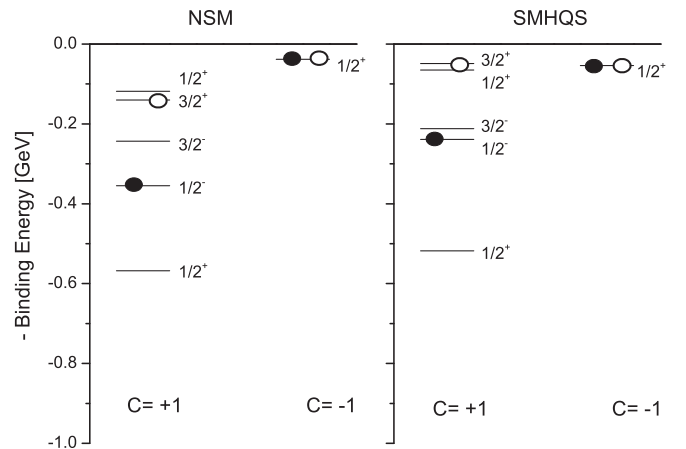


FIG. 1. Binding energies and quantum numbers corresponding to possible soliton-(anti)charmed mesons. The left panel corresponds to the spectrum obtained using the NSM formulation while the right panel to the SMHQS one. The lowest  $J^\pi = 3/2^-$  configuration is indicated by the two black circles and the  $J^\pi = 5/2^+$  by the open ones.

TABLE II. Quantum numbers and  $\mathcal{O}(N_c^0)$  masses (in GeV).

I	$k_+^{\pi+}$	$k_-^{\pi-}$	K	$J^\pi$	NSM	SMHQs
1/2	1/2 <sup>+</sup>	1/2 <sup>+</sup>	0	1/2 <sup>+</sup>	4.00	4.03
			1	1/2 <sup>+</sup>		
			1	3/2 <sup>+</sup>		
1/2	1/2 <sup>-</sup>	1/2 <sup>+</sup>	0	1/2 <sup>-</sup>	4.21	4.31
			1	1/2 <sup>-</sup>		
			1	3/2 <sup>-</sup>		
1/2	3/2 <sup>-</sup>	1/2 <sup>+</sup>	1	1/2 <sup>-</sup>	4.32	4.33
			1	3/2 <sup>-</sup>		
			2	3/2 <sup>-</sup>		
			2	5/2 <sup>-</sup>		
			2	5/2 <sup>-</sup>		
1/2	3/2 <sup>+</sup>	1/2 <sup>+</sup>	1	1/2 <sup>+</sup>	4.42	4.50
			1	3/2 <sup>+</sup>		
			2	3/2 <sup>+</sup>		
			2	5/2 <sup>+</sup>		
1/2	1/2 <sup>+</sup>	1/2 <sup>+</sup>	0	1/2 <sup>+</sup>	4.44	4.48
			1	3/2 <sup>+</sup>		
			1	3/2 <sup>+</sup>		

for the  $J^\pi = 3/2^-$  pentaquark candidate and  $(3/2^+, 1/2^+)$  for the  $J^\pi = 5/2^+$  one. In the figure the first configuration is indicated by the two black circles and the second by the open ones. In principle many other states can be obtained by populating the alternative  $C = +1$  bound states. The full list is given in Table II together with the corresponding masses up to nonadiabatic corrections. These have been obtained using

$$M = M_{\text{sol}} + 2m_D - b_+ - b_-, \quad (1)$$

where  $M_{\text{sol}} = 866$  MeV is the soliton mass,  $m_D$  the pseudoscalar charm meson mass that we take to be  $m_D = 1867$  MeV and  $b_\pm$  are the meson binding energies given in Table I.

It is seen that three low lying  $3/2^-$  with masses (4.21–4.32, 4.31–4.33) GeV for (NSM, SMHQs), respectively,

are predicted in both schemes. The rather large width found in the experiment might be explained by these 3 close lying states. On the other hand only one single  $5/2^+$  state at (4.42, 4.50) GeV is predicted.

So far we have not included the nonadiabatic contributions to the masses. To first order perturbation theory the rotational corrections can be obtained by considering

$$\frac{1}{2\Omega} \langle (I(k_+ k_-)^K)^J | (\vec{R} - \vec{\Theta})^2 | (I(k_+ k_-)^K)^J \rangle, \quad (2)$$

where  $\Omega$  is the moment of inertia of the soliton and  $\Theta$  the total isospin of the meson bound system. Moreover,  $\vec{R}$  has the role of spin of the light quark system (basically the spin of the rotating soliton, which coincides with its isospin). For a system of a  $C = +1$  and a  $C = -1$  bound mesons one has  $\vec{\Theta} = \vec{\theta}_+ + \vec{\theta}_-$ . The calculation of the matrix element in Eq. (2) requires some assumptions and/or approximations. The usual procedure in the bound state approach (BSA) to the Skyrme model [18–22] is to employ the approximation  $\langle \theta_i^2 \rangle = c_i^2 k_i (k_i + 1)$ . We denote this as BSA option. Here,  $c_i$  is the corresponding hyperfine splitting constant. As noted in Ref. [41] this approximation does not hold in the HQS limit, where it can be shown that  $\langle \theta_i^2 \rangle = 3/4$ , since for all the cases considered the bound mesons have isospin 1/2. We denote this as HQS option. Since it is not yet settled which the best way to proceed at the charm mass scale is, both cases will be considered here in order to determine the related uncertainty. The second one has to do with the way in which  $\langle \vec{R} \cdot \vec{\Theta} \rangle$  is calculated (see Ref. [42]). In fact, this term might induce mixings between states with different  $K$  and/or  $k_+$ . This effect will be neglected in what follows. The resulting formula for the rotational corrections to the mass of a system composed by a soliton and two bound mesons (one in a state with  $k_+$  and the other with  $k_-$ ) is then

$$M_{\text{rot}}(I, J, k_+, k_-, K) = \frac{1}{2\Omega} \left\{ I(I+1) + c_+ c_- [K(K+1) - k_+(k_+ + 1) - k_-(k_- + 1)] + \delta [J(J+1) - K(K+1) - I(I+1)] \left[ \frac{c_+ + c_-}{2} + \frac{c_+ - c_- k_+(k_+ + 1) - k_-(k_- + 1)}{2K(K+1)} \right] \right\} \quad (3)$$

where

$$\delta = \begin{cases} c_+^2 k_+(k_+ + 1) + c_-^2 k_-(k_- + 1) & \text{BSA} \\ 3/2 & \text{HQS} \end{cases} \quad (4)$$

Using the BSA option one recovers the mass formula given in Refs. [18,19]. Using the parameters of Table I the rotational corrections can then be calculated. Note that in the case of SMHQs scheme most of the hyperfine

splittings needed for the calculation of the rotational corrections have not been given in the literature. Thus, only the predictions as obtained in the NSM scheme are reported in Table III. The quoted values correspond to the average between the results obtained using each of the two options for the calculation of the rotational corrections. The corresponding uncertainty is considered to be half of the difference between these two values, which turns out to be about 70 MeV.

TABLE III. Masses including rotational corrections for the NSM scheme. All quoted values have an uncertainty of about 70 MeV due to the ambiguities in the formula for the rotational corrections. The lower value of this uncertainty range corresponds to the BSA option for the calculation of the rotational corrections while the upper to the HQS one.

$J^\pi$	Mass [GeV]
$1/2^+$	4.11, 4.14, 4.51, 4.57, 4.59
$3/2^+$	4.16, 4.52, 4.60, 4.60
$1/2^-$	4.30, 4.35, 4.44
$3/2^-$	4.40, 4.43, 4.48
$5/2^-$	4.50
$5/2^+$	4.64

From this table we see that the prediction for the mass of the lowest  $3/2^-$  is in the range 4.33–4.47 GeV. In the case of the  $5/2^+$  the predicted mass is in the range 4.57–4.71 GeV. Concerning the width of these states we can mention that calculating Yukawa couplings, even in light-quark systems conceived originally in the Skyrme model, has been found to be highly intricate. Thus, at this state, only general arguments based on phase space considerations can be made. In this sense we note that decay  $P_c(3/2^-) \rightarrow J/\psi p$  takes place through relative S-wave while the decay  $P_c(5/2^+) \rightarrow J/\psi p$  proceeds through relative P-wave. Thus, the  $P_c(5/2^+)$  is expected to have smaller width due to phase space suppression.

### III. CONCLUSIONS

The utility of the bound state interpretation described above is of course hinged on the existence of a  $C = -1$  meson bound state. The calculations made within the framework of the NSM approximation indicate that such a state does exist. The SMHQs approach is less definite on this issue, but most of the calculations point toward the existence of a loosely bound state in the  $C = -1$  channel. On the experimental side, the H1 experiment has found indications—so far unconfirmed by other experiments—for a narrow anticharm baryon state [43], while the earlier E791 experiment failed to find statistically significant signals for any narrow strange anticharm baryon state [44]. It should be noted that even if such state is not bound but lies close to threshold, one can still argue that an

attractive  $\bar{D}D$  interaction can make the whole soliton- $\bar{D} - D$  system bound.

Given the assumption of the existence of a loosely  $C = -1$  bound state, the existence of a pentaquark-type state with quantum numbers  $(I, J^\pi) = (1/2, 3/2^-)$  and mass in a region compatible with the LHCb observation follows naturally. Note that in the present picture at least one of the components of this state comes from populating the  $k_+^{\pi^+} = 1/2^-$  meson state. In this sense it appears as akin to the  $\Lambda(1405)$ . Note also that according to HQS such a meson bound state should be degenerate with a  $k_+^{\pi^+} = 3/2^-$  state (see Fig. 1). This probably then explains the existence of the other two  $3/2^-$  state close by. The situation concerning the  $(I, J^\pi) = (1/2, 5/2^+)$  state is less clear. The model does predict such state but the associated mass lies at about 4.6 GeV, which is somewhat too high as compared with the observed value. It has in fact been suggested that the observed peak at 4450 MeV might even be a kinematical effect [10]. In any case it is important to recall that, given the approximations made in the calculation of the masses, the quoted values have to be viewed only as first estimates.

The present model obviously predicts the existence of several other states. In particular, it predicts two  $1/2^+$  and one  $3/2^+$  states with masses in the range  $\approx 4.1$ – $4.2$  GeV, which arise by putting the  $C = +1$  meson in the lowest  $k_+^{\pi^+} = 1/2^+$  bound state. Since the decay of these low-lying states into  $J/\psi p$  proceeds preferably through relative P wave, its observation in the LHCb experiment might be hampered by phase space.

This bound state approach picture can be fairly straightforwardly extended to the bottom sector, where it would imply the existence also of hidden bottom pentaquarks in view of the large mass of the bottom mesons. This would probably require a full calculation within the SMHQs scheme, which is anyhow required to obtain more accurate predictions for the properties of the states discussed in the present work.

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